

# **Sustainable Building Materials In French Polynesia**

Final Report - May 16, 2007

Course: ER 291 – Sustainable Communities

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## **1. Introduction**

Sustainability is the capacity to balance economic, ecologic, and human resources to enable continual growth and development without compromising the integrity of each account. This principle has diverse applications and can be implemented on several levels if the proper care and attention is given. In the case of a developing economy that relies heavily on imported goods, such as French Polynesia (FP), the introduction of a sustainable system in their infrastructure has many benefits. A system for sustainable building materials has great potential to reduce energy use and pollution from energy intensive processes and shipping. It can provide suitable housing, invigorate the economy, provide local jobs, divert current waste flows, and enable a greater level of self-sufficiency. The research objective of this report is to investigate sustainable building materials in French Polynesia.

## **2. Background**

French Polynesia is the formal name for the territory of French overseas lands, which are comprised of a large cluster of islands and atolls located in the South Pacific Ocean. As a collectivity, French Polynesia has its own local executive, legislative, and judicial branches that act autonomously yet in concurrence with the republic of France. Its primary industries are tourism, pearl farming, deep-sea fishing and agriculture. The average income is \$17,500 US; however, the average cost of a single-family home is \$600,000 US [1]. This is due primarily to high land costs and costs associated with the importation of materials.

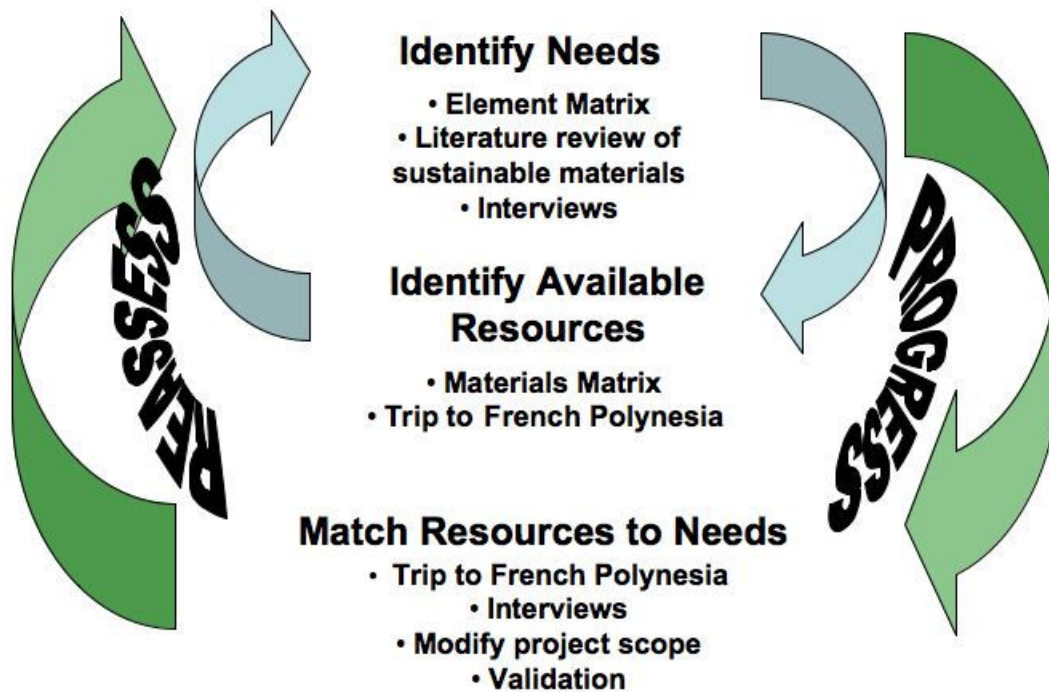
The climate is tropical, yet moderate. French Polynesia is susceptible to hurricanes, typhoons and tropical storms. In 1983, Cyclone Veena destroyed much of the housing on many of the islands. The French government responded to this crisis by developing the Fare MTR (Fare is Polynesian for house and MTR is a French acronym for Territorial Houses of Reconstruction), which is an emergency, hurricane-resistant, kit-home. With the aid of this program, 600 homes were constructed. When typhoon William hit in 1992, the kit-homes were some of the only residencies to survive. Shortly thereafter the program was revitalized with the introduction of the MTR II model. As of 1995 the MTR has been sold commercially as a type of affordable housing for French Polynesians, and is now known as the OPH House (Office of Polynesian Housing). The French government continues to subsidize 350 homes per year and sells an additional 150 homes without subsidies [1].

In a previous course, Energy & Resources 291, at the University of California at Berkeley (UCB) students focused on the climatic performance of the kit homes. Concerns from the users of the kit homes stated that the residences were too hot to remain inside during hot weather. Specific design improvements were implemented to gain an understanding how ventilation could increase performance without making drastic changes to the original design. From this data, Madelaine Fava (Project Architect) has designed a fourth prototype and enlisted the aid of the authors to provide sustainable replacements for

current building materials. This directive was the starting point for the research conducted for this report. The outcome of the investigation led the project in an alternative direction with a broader focus on the key principles of sustainability.

### 3. Approach

The final project scope is a direct result of the methodology utilized in approaching the problem statement. Iteration of a cyclic process of identifying needs, available resources, and connecting the resources to needs enabled continual development and refinement without limiting the potential for multiple solutions. Initially there was considerable interest on the part of the OPH project architect and thus the authors to utilize recycled household plastics. This material was being shipped out of French Polynesia, so using these plastic to make waterproof bathroom and kitchen paneling seemed like a great idea. During a research trip to French Polynesia, it was discovered that insufficient quantities exist for even a small-scale production. The team was concurrently pursuing other material sources; thus this news did not derail the project. The following diagram best illustrates this method:



**Figure 1:** Project Approach

Over the course of pursuing feasible options, the project scope shifted considerably. The reconnaissance trip to French Polynesia acted as the final catalyst for change as it confirmed suspicions that limiting the goals strictly in terms of the kit-home would be a

detriment and hinder the potential for real-world application. Moreover, the approach used by the authors has enabled a flexibility of project deliverables and thereby has permitted a change in scope without completely eliminating original goals and objectives. Based on the results of the research, the authors' are recommending the most viable sustainable construction material technology and a manufacturing process that will provide the most local benefit. Rather than relying on a connection to the French Polynesian kit-home, the authors have developed a plan that incorporates and emphasizes a sustainable-livelihoods mission with global environmental impact reductions. However, the relationship with the kit-home project should continue through updating the original University of California Berkeley contract with the government of French Polynesia to include a material testing phase of the proposed technologies.

#### 4. Goals

The objectives of the research conducted and the deliverables addressed within the scope of the project are as follows:

Task	Level of Goal
Identify appropriate technologies	Minimum
Prepare support package <ul style="list-style-type: none"> <li>Reviewed material to support next group</li> </ul>	Minimum
Quantify environmental indicators <ul style="list-style-type: none"> <li>Compare current and proposed systems</li> <li>Include embodied energy content (EEC), greenhouse gas (GHG) and transportation emissions.</li> </ul>	Optimum
Cost analysis <ul style="list-style-type: none"> <li>Use available schematic information to provide a comparison between current products and those proposed.</li> </ul>	Optimum
Develop schematic feasibility plans: <ul style="list-style-type: none"> <li>One island vs. multi-island plans</li> <li>Alternative energy plan.</li> </ul>	Minimum/ Optimum
Suggest new scope for contract between UCB and FP for testing of proposed material.	Optimum (Future project)
Outreach <ul style="list-style-type: none"> <li>Find champions and sustainable partnerships</li> </ul>	Minimum/ Optimum (Future project)
Future Implementation <ul style="list-style-type: none"> <li>Test program</li> <li>Pilot scale plant</li> </ul>	Optimum (Future project)

## 5. Materials Considered and Eliminated

Below is a review of materials investigated that were thought to offer possible sustainable solutions to the material needs of French Polynesia. Following the reconnaissance trip to French Polynesia these options were accordingly re-evaluated. Basic material processing requirements and mechanical properties are outlined; more in-depth information can be found in the Appendix. A summary of the Material and Element Matrices created by the authors in their investigation of the plausible materials is also contained therein. These matrices were crucial documents in the iterative approach described earlier (Figure 1).

### 5.1 Palm Oil Fuel Ash - a supplementary cementitious material

Palm oil is extracted from the fruit, copra, of the palm oil tree (see Figure 2). The oil extraction process is typically powered by electricity; however if electricity is not available then this energy can be provided by burning the palm oil tree byproducts. The process is as follows: burning the byproducts boils water, which generates steam, turns turbines, and finally creates electricity. The resulting ash, palm oil fuel ash (POFA), is 5% by weight of the original solid materials. As with other ash byproducts (*i.e.* blast furnace slag and fly ash), POFA can be used as a supplementary cementitious material due to its pozzolanic properties [2]. It has also been shown that POFA mitigates the expansive reaction of alkali-silica reaction: a common chemical attack in concrete structures [2]. In Tahiti, the fruit of the coconut palms are used to produce coconut oil. Thus, it was hoped that a similar process was used and that the resulting ash from the burning of the coconut byproducts such as husks and shells would have pozzolanic properties. Unfortunately, the sole Tahitian coconut oil producer uses electricity to power the extraction process so no ash is generated at the factory.



**Figure 2:** Cross section of a coconut. (Courtesy of Agrotechnology)

### ***5.2 Cement Composites Reinforced with Coir Fiber***

The use of vegetable fibers for reinforcing offers a unique solution to increase structural performance at a low cost with widely available materials. Fiber composite materials offer increased ductility, toughness, and post-cracking flexural strength. Coir fiber (also known as the coconut husk) is widely available in French Polynesia. This composite system is a promising yet relatively immature technology. Rigorous testing of all parameters has not been done. There is currently no manufacturing template to replicate or adapt.

The kit-homes were found to utilize exterior and interior fiber cement panels of 0.5 and 0.125 inch thickness respectively. Use of fiber in the thinner panel would not prove possible and even integration into the thicker panel would be challenging. This technology was therefore not seen as appropriate as a sustainable material across all sectors of the construction industry in French Polynesia.

### ***5.3 Recycled Plastic Products***

#### ***5.3.1: Polymeric Panels***

Polymeric panel is a term utilized to describe panels that are composed from a mix of common recycled plastic wastes such as polypropylene, polystyrene, and polyethylene. This technology can be utilized for the production of interior panels used in the construction of affordable housing units [3]. Other additives included in the mix design are carbon black for UV absorption and magnesium hydroxide for flame retardation. The primary benefits of this technology are low costs, utilization of compression molding as its mechanical transformation process, which consumes less energy than heat transformation and consumption of a waste product as the basic material component. Insufficient quantities of raw material exist to justify a building material application.

#### ***5.3.2 Cement Tiles from Recycled Plastic Wastes***

Plastic wastes are a viable component of cementitious tiles used for flooring in kitchens and bathrooms. The plastic wastes used in this technology are common recyclables, including LDPE (low density polyethylene), HDPE, and polystyrene with small amounts of PET (Polyethylene Terephthalate). Research conducted by Khatwa *et al.* evaluated several mix designs with varying plastic waste to sand ratios to determine the optimal design mix for service and mechanical properties [4]. The waste products utilized were from plastics sorted from the landfill compost using rotating screens. However, plastics diverted from a recycling waste stream can be used with greater ease. The tiles had both a low density and water absorption rate. The abrasion resistance was found to be 70% higher than most standards for cement tiles [4]. Insufficient quantities of raw material exist to justify a building material manufacturing, although this use does lend itself to ad-hoc applications.

### 5.3.3 Recycling in French Polynesia

As the above examples reveal, utilization of recycled wastes offers a possible solution for sustainable materials in French Polynesia. Such a system could reduce imports through manufacturing building materials from recycled waste generated on the islands. The additional benefit of this scheme would be the elimination of extensive shipping currently used to send the recyclables to other countries for processing. Finally recycled plastic materials are well understood and have desirable performance properties.

Unfortunately, the use of recycled waste to generate building materials was not seen as an appropriate scheme for several reasons. The major drawback to such a system is the limited amount of recyclables generated in French Polynesia (see Table 1). Although the total seems large (~ 7000 tons) this is divided among five types of recycling: paper, cardboard, plastic bottles, aluminum cans, and metal tin. When this scheme was proposed to the sole recycling organization, Société Environment Polynésien, they stated that French Polynesia did not produce sufficient quantities for such a program. The current recycling operation in French Polynesia requires the storage of recycling waste over an extended period of time simply to collect enough material to fill a cargo vessel (see Photo 1). Additional, the export shipping costs are paid by the collecting country, the recycling program remains in the beginning stages, and the regional focus is on expanding recycling outside of Tahiti and Moorea.

**Table 1:** Amount of recyclables (paper, cardboard, plastic bottles, aluminum cans, and metal tin) collected from various sources (tons).[5]

	2001	2002	2003	2004	2005	2006
Industry	1633	1989	2292	2471	2326	2653
Municipality	0	492	627	924	1065	821
Residential	1241	1935	2474	3039	2920	3102
Total	2874	4416	5393	6434	6311	6576



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**Photo 1:** Bales of sorted paper waiting for sufficient quantities to fill a cargo vessel.[6]

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#### ***5.4 Three-Dimensional Engineered Fiberboard***

The United States Forest Products Laboratory (FPL) has been investigating the application of agricultural, wood, and paper fibers for use in building materials for decades. Recently the FPL published work to introduce a new system of three-dimensional engineered fiberboard. The product can be shaped in a variety of ways. Flat and corrugated sheets are combined to create a stiff yet thin wall type module. The sheets and molded parts are made through a versatile production process that can accommodate nearly any biofiber resource. Specific study had not yet been done using coconut husk.

The major concern regarding three-dimensional engineered fiberboard is the high humidity levels in French Polynesia. Humidity in French Polynesia is extremely high; well above the optimal range of 35-55% relative humidity for an indoor environment. During the humid season, November to April, the humidity ranges from 80-90%. In the dry season, May to October, the humidity levels decrease but still will pose a performance issue for any material. The lack of residential air conditioning further compounds these issues. A sample of three-dimensional engineered fiberboard taken to French Polynesia degraded in form and strength over the course of one week due to the tropical environment. Additional durability concerns include termites and standing water. Consequently, three-dimensional engineered fiberboard was eliminated as a viable sustainable material.

#### ***5.5 Forestry in French Polynesia***

The construction industry in French Polynesia currently utilizes significant amounts of wood imported from the United States and Canada. Kit-homes in Moorea were found to utilize both Douglas fir and pine. Two types of locally grown wood were investigated as possible alternatives. The abundance of coconut trees is seen by some government officials as a viable material source that would provide jobs and an end product in the outer atolls.[7] However, experts in the wood industry suggested that a production mill would not be financially viable supporting more than a few workers[8]. Further, due to dimensional constraints, the wood obtained from the coconut trees would only be appropriate as a finish material and not structural elements.

The Caribbean Pine was considered as another alternative. Plantations of Caribbean Pine were started in 1977 to create a source of locally grown wood; however the results are not overwhelmingly positive. Contractors in the building industry state that these products are difficult from a workability perspective. Pre-drilling is required for Caribbean Pine as nailing the dense wood is impossible. Thus the time and effort to build using these materials is significantly increased. However, in outdoor settings where durability is a crucial concern this material has been proven appropriate in French Polynesia (see Photo 2).



**Photo 2:** Caribbean pine used as decking material in a kit-home in French Polynesia.[Error! Bookmark not defined.]

Finally, other local woods and bamboo were investigated. Various additional woods exist, but are only suitable for handcrafts. Bamboo, a member of the grass family, is not seen as a desirable material by the majority of the population. However, a few families continue to utilize bamboo as a building material. The high cost of bamboo in French Polynesia is not comparable to lower priced product in Bali. Overall the lack of demand reveals bamboo as an inappropriate solution.

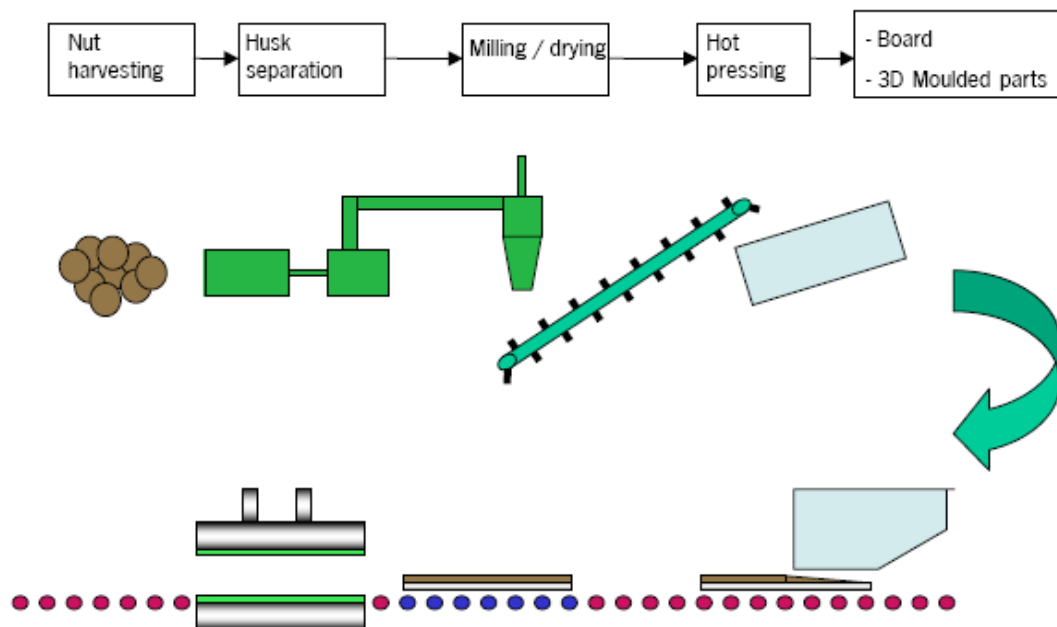
## 6. Chosen Material: Coir Binderless Board

During the extensive literature review conducted for this report, several systems of panel construction were considered. Of the technologies evaluated, one particular coconut husk construction board seemed especially promising. Due to the responses of those interviewed during the research trip to French Polynesia and other findings there, the “coir binder-less board” system was determined to be promising enough to pursue a preliminary study. At its core this is a relatively mature technology; a feasibility study for large-scale production of a similar system was performed in Sri Lanka in 1978 [9]. The most recent version of the coir board product was developed by the Agrotechnology laboratory in Wageningen, The Netherlands under the direction of Dr. Jan Van Dam. Funding was provided by the United Nations (UN) via the Common Fund for Commodities and was administered through the Food and Agriculture Organization (FAO). The UN intends to make this technology freely available to all coconut producing countries. Currently, manufacturing facilities are in the advanced planning stages for the Philippines and Indonesia. A successful pilot-scale plant operates in the Philippines, where a technology transfer workshop will be held this June (2007) to establish a transfer protocol. Consequently, this is a well-established technology with good technical and administrative backing.

The material science technology of the board is very simple and elegant. Coconuts are about 35% coir (or coconut husk) by weight (see Figure 2). This is a heterogeneous material made up of about 30% fiber and 70% pith intermingled. The pith is rich in lignin which when heated under pressure exhibits thermosetting behavior. Therefore it makes a strong, stable, and resin-like binder. The fibers, typical of natural fibers exhibit

strengths exceeding steel (on a per mass basis). The coir contains both of the elements needed for a strong, dense building panel [10].

The manufacturing process is simple as shown in Figure 3. Coir is dried and ground to yield fibers within a certain range of length. The ground material is formed into molds for the desired product shape. Heat and pressure are applied to bind the material together. Maximum strength is achieved using a temperature of 180°C. Pressure and hold times were found to be less important and can range between 300-750 kN and 3-30 minutes respectively. A variety of densities can be formed on the same equipment simply by altering the temperature, pressure and hold times. Low density boards ( $1050 \text{ kg/m}^3$ ) are applicable for interiors, while the high density boards ( $1350 \text{ kg/m}^3$ ) are strong and durable enough for exterior use. Table 2 summarizes the key material properties.



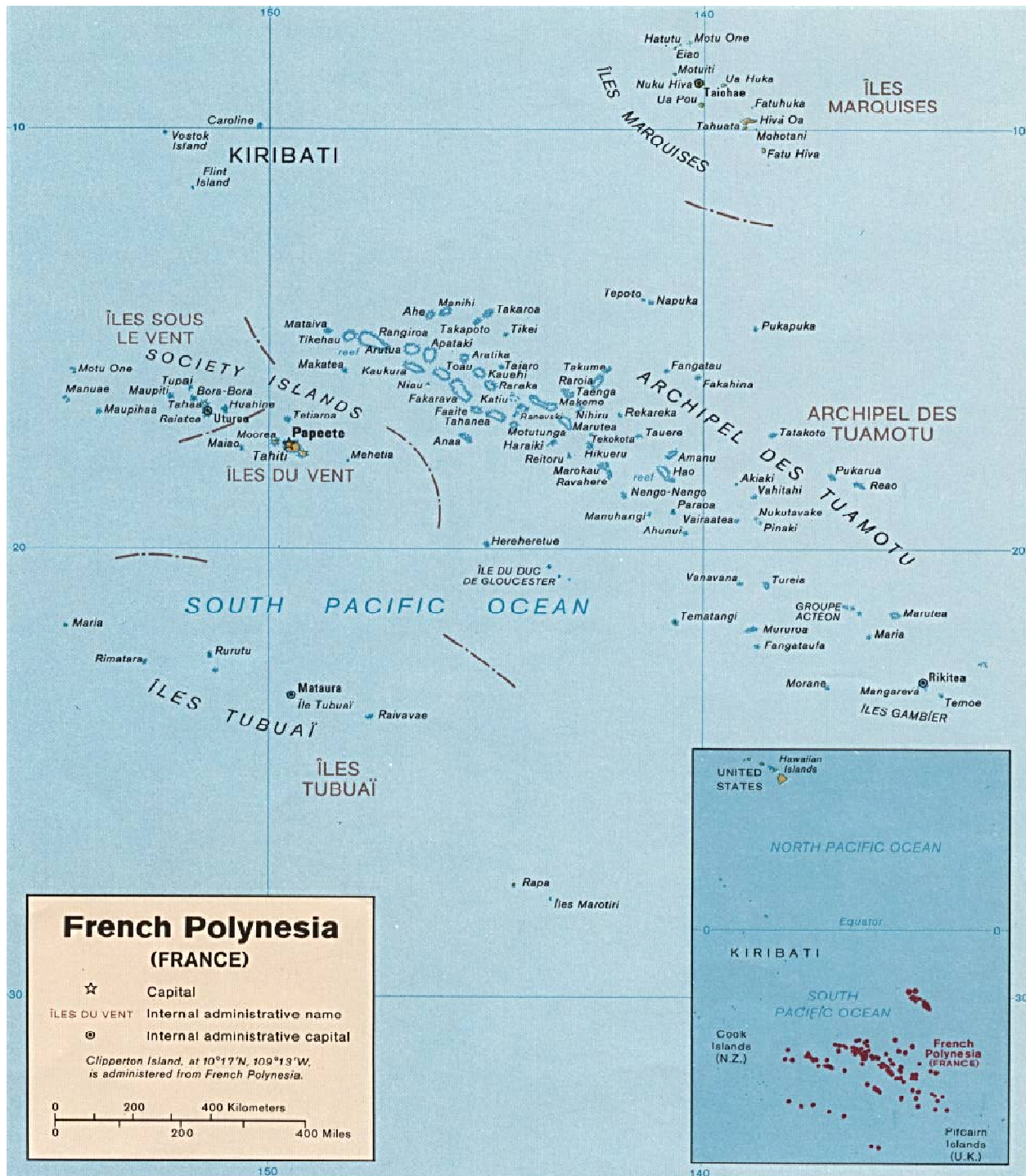
**Figure 3:** Coir board manufacturing process. (Courtesy of Agrotechnology)

The only known drawback to the boards is that the high-density panels require pre-drilling and cannot be nailed. This is similar to Multi Density Fiber Board products. While not ideal, this workability issue is not as serious as it is for the Caribbean Pine dimensional lumber simple because of normal construction sequences. It is very difficult to attach panels to a timber frame that is predrilled because this is a blind connection. Predrilling the coir panels and screwing them to a softwood timber frame is relatively simple, yet it does add a step. This step could be mechanized.

**Table 2: Coir Board Properties**

<b>Coir Binderless Boards*</b>		
	Medium Quality Boards	High Quality Boards
<b><u>Properties</u></b>		
Density kg/m <sup>3</sup>	1,050	1,350
Moisture content (%)	9	9
Bending Strength (Mpa)	13	47
Bending Stiffness (Gpa)	2	5
Water Resistance	poor	good
Fire Resistance	good	good
<b><u>Handling &amp; Workability</u></b>		
Sawing	ok	ok
Sanding	ok	ok
Painting	ok	ok
Drilling	ok	ok
Screwing	ok	after predrilling
Nailing	ok	NO

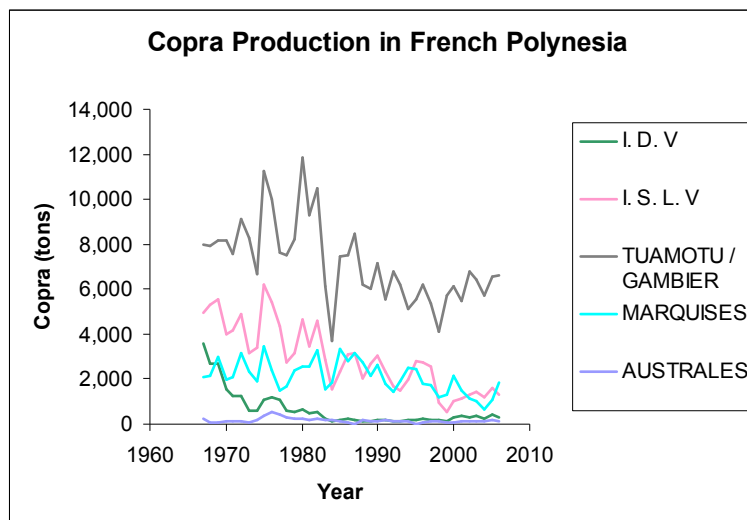
\*Table courtesy of Agrotechnology



**Figure 4:** Map of French Polynesia illustrating the various island groups.[11]

## 7. Environmental Analysis of Coir Binderless Boards

The concept of sustainable materials in island communities offers the unique possibility for creating local sustainable livelihoods. As migration to urban centers, mainly Papeete on Tahiti, has grown over the years, keeping local communities in the outer islands of French Polynesia has become a continual challenge for the French Polynesian government. The main source of employment for numerous people in these remote islands is the production of copra, which is highly subsidized by the French government. The world market price for copra is 20 French Polynesian Francs/kg, but in French Polynesia the rate is 100 French Polynesian Francs/kg. Despite the high subsidies, the production of copra in all the island groups has shown significant decline over the past 40 years (see Figure 5). As land prices have increased dramatically in tourist and urban areas (*e.g.* Moorea and Tahiti in Iles Du Vent), large scale coconut plantations are no longer profitable. The decrease in copra production in the outer islands has been less drastic. The use of a coconut byproduct would prove instrumental in the revitalization of this industry, while providing local jobs and a value added by-product.



**Figure 5:** Production of copra in the various island groups of French Polynesia.  
(Note: I.D.V.- Iles Du Vent, I.S.L.V.- Iles Sous Le Vent).[12]

### 7.1 Comparison to Engineered Woods

Coir board was identified as the most appropriate sustainable material for use in French Polynesia. Pressing of the husk material from coconuts creates the coir board as explained in the material investigation section. Currently, the husks are viewed as a waste product and are burned as a means of disposal. Carbon dioxide savings would be realized by ending this practice. A small percentage of husks are used as a growth medium for horticulture as well. While the Intergovernmental Panel on Climate Change considers burning renewable biomass carbon-neutral, using the husks instead of burning them is in effect a form of carbon sequestration.

The coir binderless panels compare very well on environmental terms to the engineered woods currently imported to French Polynesia. Table 3 shows cradle-to-gate<sup>1</sup> GHG emissions data for engineered woods and the coir panel [13]. There are two possible scenarios for the coir panel; one assumes diesel fuel powers the production process, whereas the other scenarios utilize 100% coconut oil. Even the diesel powered system emits only 13% of the GHGs attributed to the imported engineered panels, when compared by weight. When compared by volume, the percent of average emissions jumps up to 33% which reflects the higher density of coir boards. This is largely due to the fact that 100% of the coir panel's raw material is a waste product.

**Table 3:** Emissions data for imported engineered woods [13] and coir boards

<b>Emissions* as CO<sub>2</sub> Equivalent (CO<sub>2</sub>E) ** for US manufactured Plywood and Oriented Strand Board (OSB) and local COIR board</b>			
Product and source area	Product Density kg/m <sup>3</sup>	CO <sub>2</sub> E by volume kg CO <sub>2</sub> E/m <sup>3</sup>	CO <sub>2</sub> E by mass kg CO <sub>2</sub> E/kg
<u>Plywood (avg.)</u>	518	332	0.64
Pacific NW	480	235	0.49
South East	555	429	0.77
<u>OSB</u>	651	780	1.2
<b>Total Average</b>	562	<b>481</b>	<b>0.92</b>
<b>Coir Board using diesel***</b>	1,356	<b>157</b>	<b>0.12</b>
<b>Coir values as % of avg Coir Board using coconut oil</b>	241%	<b>33%</b>	<b>13%</b>
	1,356	<b>0</b>	<b>0</b>
*Does not include transportation to or within French Polynesia			
**Does not include biomass combustion, CO, SO <sub>2</sub>			
*** 0.75 kg of CO <sub>2</sub> /KWh			

<sup>1</sup> Includes everything involved with acquiring raw materials, transportation to manufacturing unit, and all operations in manufacturing. Gate refers to the gate of the factory.

Similar to the total GHG data, the embodied energy content (EEC) of the coir binderless boards is much lower than plywood or oriented strand board (OSB). In Table 4 cradle-to-gate EEC data is presented [14]. Since the coir panels are made of a waste product, the related EEC is entirely from the process energy required. Both plywood and OSB use large amounts of non-renewable resources in the binders; OSB uses the highest quantity whereas the coir panel uses none. Comparing the products, the coir panel has only 5% of the EEC attributed to the imported panels, when compared by weight. When compared by volume, the percent of average again jumps up to 11%, which reflects the higher density of coir boards.

**Table 4:** Embodied energy data for imported engineered woods [13] and coir boards

<b>Embodied Energy Content* for US manufactured Plywood and Oriented Strand Board and local COIR board</b>					
Product and source area	Product Density kg/m <sup>3</sup>	MJ/m <sup>3</sup>	MJ/kg	KWh/m <sup>3</sup>	KWh/kg
<u>Plywood (avg.)</u>	518	4,644	8.88	1,290	2.47
Pacific NW	480	3,638	7.58	1,011	2.11
South East	555	5,649	10.18	1,569	2.83
<u>OSB</u>	651	11,145	17.12	3,096	4.76
<b>Total Average</b>	562	<b>6811</b>	<b>11.63</b>	<b>1892</b>	<b>3.23</b>
<b>Coir Board**</b>	<b>1,356</b>	<b>751</b>	<b>0.55</b>	<b>209</b>	<b>0.15</b>
<b>Coir values as % of avg</b>	<b>241%</b>	<b>11%</b>	<b>5%</b>	<b>11%</b>	<b>5%</b>
*Does not include transportation to or within French Polynesia					
**EEC reflects work to manufacture board only as all source material is recovered waste					

## 7.2 Current Environmental Costs of Husk Disposal

The burning of waste husk from copra production creates a significant amount of CO<sub>2</sub> emissions. This can be eliminated through the diversion of the waste stream into the production stream of the coir board. The possible reduction of CO<sub>2</sub> by the implementation of coir board plants in French Polynesia was determined by a series of energy conversion calculations combined with stoichiometry. Basically, the average energy content of crop wastes (assuming 20% moisture content) was converted to energy per tonne of coal and then translated to CO<sub>2</sub> emissions by balancing the combustion equation of bituminous coal in air [15]. For the derived equation see Equation 1.0.

**Equation 1.0:** Conversion of Husk Waste (kg) to CO<sub>2</sub> (kg)

$$kg_{husk} \times \left[ \frac{13 \times 10^{-3} GJ}{kg} \right] \times \left[ \frac{3.57 \times 10^{-2} MT_{coal}}{GJ} \right] \times \left[ \frac{1000 kg}{MT} \right] \times \left[ \frac{0.44 kg CO_2}{0.16 kg_{coal}} \right]$$

$$\Rightarrow kg_{husk} \times 1.276 \Rightarrow kg CO_2$$

The conversion rate of 1.276 kg of CO<sub>2</sub> released per every kg of husk burned is utilized in the calculation of emissions saved. The quantity of husk burned is extracted from real data of current copra production within French Polynesia. From this information, the authors determined that the emissions saved would be based on the husk collected from each proposed shipping route (refer to Section 7.4 – Implementation Plan for results).

### 7.3 Transportation Factors

Currently, a majority of construction materials are imported to French Polynesia from Oregon, Canada, and France. Thus these materials have high associated emissions and embodied energy costs. The assumed average emission of CO<sub>2</sub> per kilometer traveled per tonne of freight by long haul sea shipping is 0.0175 kg CO<sub>2</sub>/km-kg [16]. Assuming that the proposed production output of coir board for one medium sized plant (20,000 tonnes) will displace an equal amount of cargo containing building materials. The corresponding distance and conversion of CO<sub>2</sub> emissions for the three routes are presented in Table 5.

**Table 5:** Long Haul Transportation Contribution to CO<sub>2</sub> Emissions per Cargo Displaced per Plant

Route	Distance (km)	CO <sub>2</sub> Emission (MT)
Oregon to Tahiti	7,230	2,530
Canada to Tahiti	8,000	2,800
France via Panama Canal to Tahiti	16,500	5,775

### 7.4 Implementation Plan

The system currently in place for the production of coconut oil is the model for our suggested coir board system. Ferries from Tahiti transport both passengers and cargo to the outer island communities. The main port of French Polynesia is located in Papeete, Tahiti. Copra is collected on the individual islands and then taken to the local port where the individual is paid for their product. The ferry continues along its route collecting copra along the way. Finally, the ferry arrives in Papeete where the oil production takes place. In a similar manner we suggest utilizing the cargo/passenger ferries as a means of transporting the husks.

Contrary to coconut oil production, we suggest that the coir boards are manufactured in the outer islands. This would create a source of employment and reduce the

transportation of high volume material. The final boards could be used on the island where they are produced or taken to Tahiti or Moorea to be sold as a building material. As the cost of each manufacturing plant is substantial, \$2 million US, it would not be appropriate to build a mill on every island that produces coconuts. Selected locations throughout French Polynesia would enable the utilization of husk from neighboring islands and the existing ferry system. Not all islands have active coconut plantations and it is necessary to quantify the amount of husks available before making a final recommendation.

The island of Tahaa in the island group Iles Sous Le Vent is the dominate producer of copra in French Polynesia with over 770,000 kg produced per year (see Table 6). The majority of the other top five producers are located in the Marqueses, which lie around 1450 km away from Tahiti compared to only 523 km for the Tuamotus, and 200 km for Tahaa (see Figure 4). The varied location of these islands doesn't lend itself easily to one simple route.

**Table 6:** Top 5 copra producing islands in French Polynesia as of 2007.[12]

Island Group	Island	Price per kg (French Polynesia Francs)	Value*	Net Weight (kg)
Marqueses	HIVA OA	100.00 F	45,033,675 F	442,921
Marqueses	NUKU HIVA	100.00 F	39,344,925 F	385,594
Tua Ouest	RANGIROA	100.00 F	40,634,545 F	362,336
ISV	TAHAA	100.00 F	79,996,955 F	773,195
Marqueses	UA HUKA	100.00 F	46,175,565 F	442,885

\* Total value includes a portion of seconds sold at a lower price

As the goal is to reduce greenhouse gas emissions, short ferry voyages and large quantities of husks acquired per kilometer travel are desirable. Simple routes that focus on the major island groups were thus evaluated to determine the quantity of husks gathered and the required kilometers traveled (see Table 7). Note that these routes are merely suggested routes and currently no ferry or vessel follows these programs. However, if the industry were to become viable these suggestions should be considered by such companies. The islands considered produced more than 100,000 kg of copra per year as a base line. A more detailed description of the islands included, quality of husks, route suggest, *etc.* is presented in the appendix. The kilometers traveled assume the beginning and final port is in Tahiti.

**Table 7:** Possible ferry routes for islands producing more than 100,000 kg copra.[12]

Proposed Routes within Island Groups Producing > 100,000 kg of copra						
Route	Island Group	Husk (MT)	Distance (km)	Husk/Distance (MT/ km)	Freight CO <sub>2</sub> (MT)	CO <sub>2</sub> Burning Husks (MT)
1N	IDV/ ISLV	5,018	523	<b>9.595</b>	46	6.40
2N	Marquises	6,179	3,258	1.897	352	7.88
3N	Tuamotu Center	2,819	2,092	1.347	103	3.60
4N	Tuamotu East	4,539	3,379	1.343	268	5.79
5N	Tuamotu West	6,974	1,529	<b>4.561</b>	187	8.90
6N	Tuamotu North-East	2,326	2,574	0.904	105	2.97

(N- new route)

From the analysis Route 1N and 5N offer significant amounts of husk per distance traveled. The higher this value the better the return of material per unit greenhouse gas and the lower the transportation cost. Route 1N includes several islands in Iles Du Vent and Iles Sous Le Vent of which Tahaa plays a crucial role. As production levels in Tahaa are high and the distance to Tahiti is short this Route offers significant opportunities. The Tuamotu West route (5N) also is favorable in the above scenario. For Route 1N, based solely on amount of husk produced on each island the most appropriate location for a manufacturing plant would be Tahaa and/or Raiatea. The second best option would be Route 5N where a plant could be placed on Rangiroa and/or Kaukura.

While focusing on local island groups seems logical, it might prove more beneficial in the short term to utilize existing ferry services offered [17]. Similar to above, the existing routes all begin and end in Tahiti. Thirteen different existing routes were examined and the husk content, miles, and husk per distance traveled were calculated (see Table 8). Detailed information can be found in the appendix. For existing routes the best husk to distance ratio is Route 11E with 2.659 MT/km versus Route 1N with 9.595 MT/km. However, this ratio must be examined in relation to the total amount of husk produced. Although Route 11E has a high husk/distance ratio, only around 2,675 MT of husk would be gathered versus Route 12E where over 10,752 MT would be collected; an increase of 4 fold. An additional benefit of having a plant on a route with a higher quantity of husks would be the increased production capacity of the plant.

Thus Route 1E, 5E, 6E, 11E, and 12E would be appropriate locations for a manufacturing system based on current ferry routes. Location of the plant(s) could be Ua Huka/ Hiva Oa, Rangiroa/ Kaukura, Reao/ Puka Puka/ Fakahina, Rangiroa/ Kaukura and Reao/ Tataoto/ Puka Puka respectively. These choices were made based upon which islands in each respective route produced the most husks. All these plant locations overlap with islands visited on the new suggested routes, creating an appropriate layout for production. Consequently, plants built on one of these locations would prove viable in the short and

long term for either the existing or proposed ferry scheme. Finally it should be mentioned that none of the existing routes that travel to numerous islands stop by Tahaa. It is assumed that there is only direct service between Tahaa and Tahiti. As Tahaa is the largest producer of coconut husks it would be crucial to implement Route 1N at a minimum.

**Table 8:** Current ferry routes and associated husk production in French Polynesia. [12]

Existing Ferry Routes in French Polynesia					
Route	Husk (MT)	Distance (km)	Husk/Distance (MT/ km)	Freight CO <sub>2</sub> (MT)	CO <sub>2</sub> Burning Husks (MT)
1E	7,887	3,500	<b>2.253</b>	483	10.06
2E	1,341	925	1.450	22	1.71
3E	1,800	1,126	1.599	35	2.30
4E	1,285	1,448	0.887	33	1.64
5E	2,676	1,126	<b>2.377</b>	53	3.41
6E	10,195	4,143	<b>2.461</b>	739	13.01
7E	7,482	3,821	1.958	500	9.55
8E	2,367	3,138	0.754	130	3.02
9E	1,391	925	1.504	23	1.77
10E	1,285	1,448	0.887	33	1.64
11E	2,675	1,006	<b>2.659</b>	47	3.41
12E	10,752	4,787	<b>2.246</b>	901	13.72
13E	4,340	3,990	1.088	303	5.54

(E – existing Route)

## 8. Production scenarios

### *8.1 Individual islands have husk milling capacity and may be power independent*

This scenario would allow individual farmers to add value to the husk waste product through primary processing. It is estimated that grinding adds \$20US/tonne to the husk [18]. Milling on site lowers the volume per kilogram of material, which is advantageous for transportation. The main technical challenge to this approach is to insure quality control such that milled husk size is within given tolerances at all sites. Below various scenarios are given for powering the equipment. The authors suggest that all equipment be owned by an island cooperative, with farmers paying a fee for use based on quantity.

- i. Mechanized grinder-mill with power options:
  1. “Grid” Electricity powers electric grinder (only Tahaa)
  2. Diesel electric generator
    - a. diesel fuel
    - b. coconut oil
  3. Diesel motorized grinder
    - a. diesel fuel
    - b. coconut oil
- ii. Manually powered grinder-mill for smallest scale

For the smallest scale production, a hand or pedal cranked grinder may be sufficient. Most islands in the Tuamotus and Marquise do not have grid-connected electricity. Electricity is normally provided by diesel generators. Motorized husk grinders also run on diesel. This opens up an opportunity for the islanders to reduce their reliance on imported fuel. Many diesel engines can be run on vegetable oil without conversion. At 42 MJ/kg coconut oil has a fuel value nearly equivalent to petroleum diesel (45MJ/kg). Using coconut oil as a fuel is compatible with simple engines such as those found in generators and industrial equipment, as opposed to those found in cars. The higher viscosity of coconut oil, makes it unsuitable for use in cold engines, therefore a small amount of diesel would still be required to get the engine started. At temperatures below 22°C coconut oil starts to solidify, so some passive solar storage containers (*i.e.* vessels painted flat black) are a good idea.

Coconut oil could be pressed from copra on small-scale manual or mechanized presses currently available. A promotional video by the Thai government features a manual press [19]. The biggest obstacle for this plan is diverting copra from sales. The current subsidies raise the retail price of copra from \$0.22 US per kilogram to \$1.10/kg. In 2004, the average retail price of diesel fuel in French Polynesia was \$1.10/L [20]. Copra has an oil content of approximately 70% and coconut oil has a density of 0.925 kg/L. The conversion of 1 kilogram of copra produces 0.7 kilogram of coconut oil, or 0.76 liters of oil. This is equal to 0.82 liters (0.76x1.08) of diesel fuel. At \$1.10/L for diesel, the coconut oil is worth \$0.90/kg of copra.

With the current copra subsidy (\$1.10/kg) coconut oil fuel costs \$1.56/L, 42% higher than diesel. Thus without a reduction in the current subsidy this scheme is not likely to be adopted. However, all calculations are based on available retail values, if wholesale values for copra and diesel were known this might change the economic outcome. Also, other factors such as increased energy independence and the possibility for enhanced value to second quality copra might make the scheme attractive even with the current subsidy.

### ***8.2 Central island receives un-milled husks; may be power independent***

This scenario allows for greater quality control but may increase transportation costs and removes the added benefit to individual farmers. The prospect of utilizing coconut biofuel may be facilitated by centralization because oil could be produced in larger volumes and technicians from plant operations might be more capable of maintaining the equipment. Below various alternatives for equipment power source are given.

- iii. Mechanized plant equipment: grinder-mill/former/press with power options:
  - 1. “Grid” Electricity powers electric grinder (only Tahaa, others?)
  - 2. Diesel electric generator
    - a. diesel fuel
    - b. coconut oil
  - 3. Diesel motorized grinder
    - a. diesel fuel
    - b. coconut oil

Referring to Figure 6, 1 kilogram of copra can be converted to 29.4 MJ or 8.17 KWh of energy. Therefore, coconut oil is worth about 10.75KWh/L. A small grinding machine has about 15 horse power (HP) and grinds about 225 kilograms of husks per hour – which translates to an energy demand of about 50 KWh/tonne of husk. Under this scenario, 163 kilograms of husk can be milled per kilogram of copra processed for fuel oil. Estimates are not based on precise equipment specifications; however, the values likely give an accurate order of magnitude.

An annual production of 20,000 tonnes of board material requires 20,500 tonnes of husk. For 7,600 hours of annual manufacturing time, the processing equipment must have the capacity move 2.7 tonnes of husk per hour (demanding about 180 HP). Assuming that the other major two steps in the board manufacturing process (forming and pressing) have similar energy demands, the total processing energy required is on the order of 150KWh per tonne of husk. The 2.7 tonne/hr load could be fueled with 37.7 L of coconut oil/hr, equivalent to 18.4 kg of copra. The annual demand for the entire process is 3,078 MWh/yr corresponding to 1,800 barrels of oil (286 kiloliters).

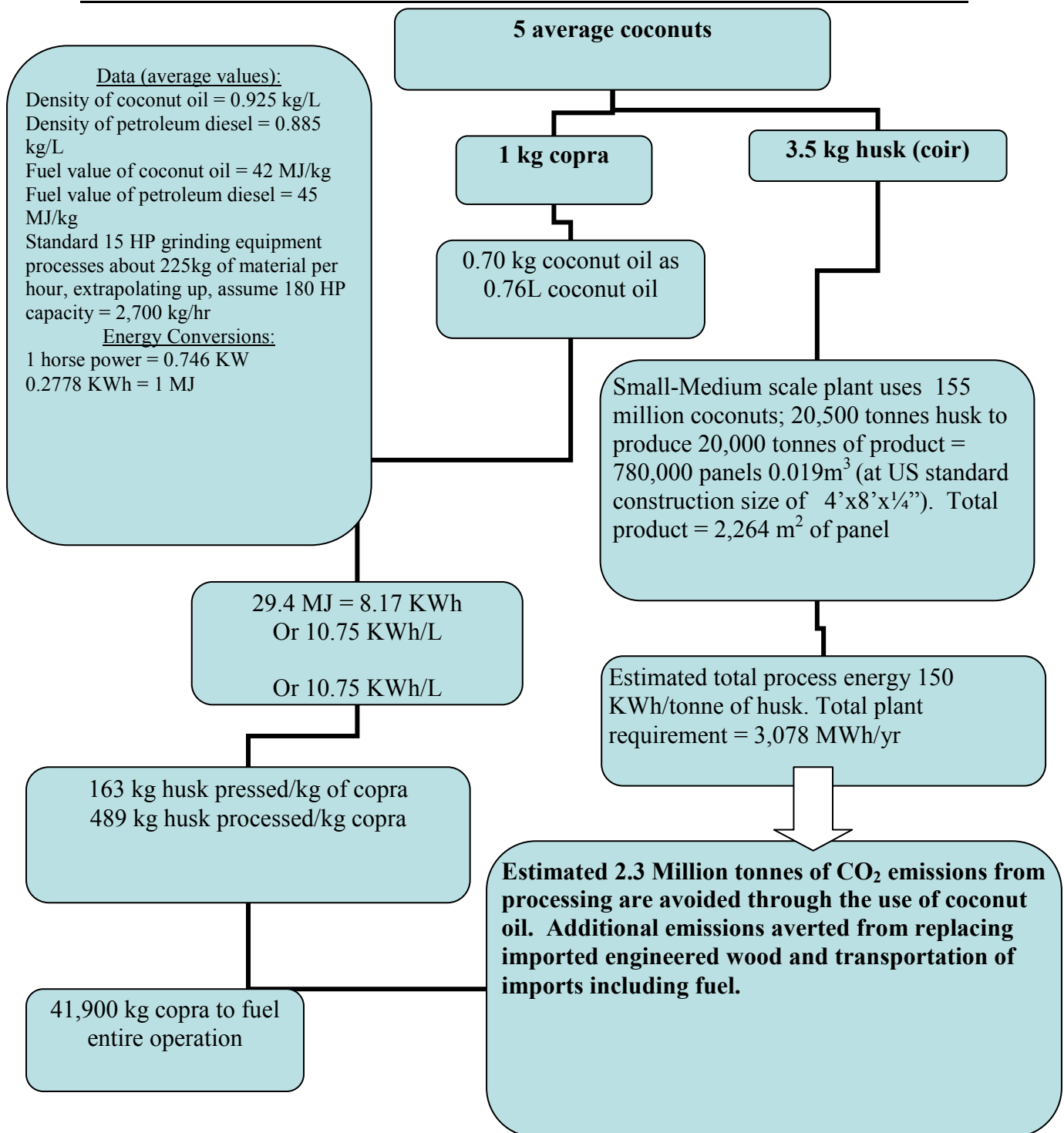
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One of the primary features of using coconut oil is the offset of green house gas emissions. As a carbon neutral bio-fuel (per IPCC<sup>2</sup>), significant carbon emissions could be avoided for every liter of diesel fuel replaced. The use of diesel has a direct emissions factor of 2.67 kg of CO<sub>2</sub>/L of fuel – this translates into approximately 3 kg of CO<sub>2</sub>/kg of diesel [21]. More relevant to the island use, according to the IPCC [22] the commonly accepted figure for diesel generators is 0.75kg of CO<sub>2</sub>/KWh produced with diesel. To produce 20,000 tonnes/yr uses 3,078 MWh/yr -- if all energy was sourced from coconut oil, about 2.3 Million tonnes of CO<sub>2</sub> emissions are averted.

It is important to note that this does not even include bunker fuel emissions from the transport of the fuel to the outer islands. The total offset of GHG emissions could eventually be sold on the emerging and inevitable carbon markets. Currently values range from a low of US \$5/tonne to over \$25/tonne. This is definitely an area to watch as policy changes and other drivers of this market are poised for major changes.

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<sup>2</sup> Intergovernmental Panel on Climate Change



**Figure 6:** Flow diagram from coconut to oil, husk, power, and building panel.

By using coconut oil fuel 2.3 Million tonnes of averted CO<sub>2</sub> emissions is possible – this is equivalent to 60 million tree seedlings grown for ten years [23]. These emissions savings translates into 115 tonnes of CO<sub>2</sub> averted per tonne of panels produced, and 155 tonnes of CO<sub>2</sub> averted per cubic meter of panels. To account for total emissions per panel one must consider additional emissions due to averted crop burning, transportation of goods and fuel and averted use of energy intensive materials. For a summary with integrated emissions data see section 9 – Net Emissions.

**Table 9:** Coconut oil fuel plan to avert emissions

<b>Averted CO<sub>2</sub> Emissions - Coconut Oil Fuel Plan*</b>		
	<b>by mass</b>	<b>by volume</b>
<b>Coir Board energy Demand</b>	<b>tonnes CO<sub>2</sub> per tonne of boards</b>	<b>tonnes CO<sub>2</sub>/m<sup>3</sup> of boards</b>
<b>154 KWh/tonne</b>	<b>115</b>	
<b>208 KWh/m<sup>3</sup></b>		<b>155</b>
*Diesel CO <sub>2</sub> emissions=0.75 kg/KWh; coconut oil is carbon neutral		

For either scenario it is important to note that suitable equipment is available used on the world market. For grinders, prices range from below \$170 for small and manual models to over \$1,700 for large capacity equipment [24]. Some of the machinery is similar to or could be converted from copra production equipment. A quick web search brought up many sources of equipment, including a grinder up for auction in New Zealand [25], (see Figure 7). Indonesia is facing a major down turn in their plywood production (due to a rise in electricity cost and log supply issues) and is therefore a possible supplier of used pressing equipment [26].



**Figure 7:** Grinder for auction [25]

## 9. Net Emissions

The culmination of the research on emissions is summarized through a comparison of lifecycle emissions of OSB/plywood to Coir Board (produced with either diesel or coconut oil). The resulting emissions are shown in Table 10 below.

**Table 10:** Net Emissions for Lifecycle of Building Product

Material	Production CO <sub>2</sub> (MT)	Import CO <sub>2</sub> (MT)	Local Distribution CO <sub>2</sub> (MT)	Husk Burning CO <sub>2</sub> (MT)	Total CO <sub>2</sub> (MT)
OSB/Plywood	18,400	2,625	0	27	21,052
Coir Board, diesel	2,400	0	1,640	0	4,040
Coir Board, coconut oil	0	0	1,640	0	<b>1,640</b>

The following assumptions were made: the production value is for 1 plant with a 20,000 MT capacity, 20,000 MT of imported plywood is used as a comparison, there is a 1:1 conversion of husk to coir board, import distance is 7,500 km (from Northwest US to

French Polynesia), and lastly, local distribution uses existing route 6E and 12E for coir board only.

## **10. Material Supply**

Consistent material supply will be critical to ensure a profitable business model. Luckily, coconuts are harvested from the trees at varying intervals throughout the year. The fruits are produced all year, but seasonal rainfall can alter the amount produced. Periods of greater rainfall correspond to greater yields of coconuts. In the South Pacific mature coconuts are not harvested by hand. Only when the nuts fall to the ground are they collected and processed. Additional research should be done in this area as the final stages of implementation approach.

## **11. Material testing**

The University of California Berkeley operates the Gump Research Station in Moorea, French Polynesia. Previous researchers at the Gump Research Station investigated the climatic attributes of the existing kit house (Office of Polynesia Housing: OPH), and redesigned the house using computer modeling.[27] Changes were made to improve ventilation for a more comfortable indoor atmosphere temperature during warm weather. A contract was made between the Gump Station and the French Polynesian government that allows for the collection of in situ data to confirm the computer modeled findings. The research is to be conducted in an OPH built on the grounds of the Gump Station. The OPH has not been built yet.

We would suggest expanding the scope of the experiment to account for materials testing as well. The necessary coir board could be obtained from Agrotechnology of Wageningen in the Netherlands or one of their partners in productions. Incorporating this material into the building would provide empirical results on issues of durability, ease of use, construction issues, and many other concerns. Further, the materials research would also act as an exhibit for local builders. The experiment would limit the financial risk to builders associated with using a new material, as the exhibit would reveal how the material behaves in a local climate and environment. Material testing would be completed after the completion of the climate analysis.

There are several unique issues that should be monitored to evaluate the material. As discussed previously, the humidity in French Polynesia is extremely high. The material testing should reveal high performance levels in such a climate. Finally, issues of termites and standing water must be investigated as well. Appropriate physical barriers for termites, waterproofing, and drip edges should also be investigated during material testing to improve the detailing of the new design.

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## **12. Cost Comparison**

Finally, cost comparisons are crucial to validate the financial sustainability of such a product. Cost analysis for coir versus plywood, oriented strand board (OSB), and fiber cement boards should be undertaken. The cross analysis looks at standard sheets of plywood (4'x8'x0.25" and 0.5" or 1.2m x 2.4m x 8cm and 15cm) and fiber cement boards (4'x8'x0.25" and 0.5" or 1.2m x 2.4m x 4cm and 15cm). Unfortunately, local prices for plywood and OSB could not be obtained, so the costs were estimated according to current global world market values and a 20% shipping markup, yielding a \$300/m<sup>3</sup> cost or \$6.00 per panel.

For the cost comparison of a panel of coir board to a panel of OSB or plywood, a single medium sized scale plant was used to determine the necessary retail market cost of coir board to a) breakeven and b) earn a 25% return on initial investment in one-year time.

### ***11.1 Initial Investment***

According to an economic study and financial data provided by Agrotechnology, the initial capital investment or a medium sized coir board production plant with a production capacity of 15,000 m<sup>3</sup>/yr is \$2.0 million US. This production capacity is equivalent to producing 750,000 panels/yr of similar size to the compared case of OSB & plywood panels.

### ***11.2 Operating Costs***

Four major expenses must be considered when calculating the operating cost of the coir board production plant. These expenses are overhead, labor, materials, and cost of running equipment. An overhead (insurance, office expenses, etc.) of \$50,000 is assumed at 10% of the total annual revenue of \$500,000/yr. Labor expense for 8 workers is \$160,000/yr. Material costs at this point are considered to be negligible because coir is currently a waste product with no current market value and also assuming that current shipping routes will be utilized for collection. Lastly energy costs are determined to be \$1.23 million/yr for an electricity grid connection or \$307,800/yr for a diesel or coconut oil generator (refer to Appendix for detailed calculations of all operating costs).

### ***11.3 Breakeven Cost***

To breakeven in year 1 of operation, the cost per panel is calculated in the Table 11 below (assuming production capacity of 750,000 panels/yr):

**Table 11:** Cost per Coir Board Panel for Breakeven Scenario

Power Supply	Initial Investment (\$)	Operating Cost (OH, Labor, Materials) (\$)	Energy Cost (\$)	Cost per Panel (\$)
Grid Connection	2,000,000	210,000	1,230,000	4.60
Generator	2,000,000	210,000	307,800	3.36

#### **11.4 Twenty-five Percent Return Cost**

To earn a 25% return on the initial investment in year 1 of operation, the cost per panel is calculated in Table 12 below:

**Table 12:** Cost per Coir Board Panel for 25% Return Scenario

Power Supply	Initial Investment (\$)	Operating Cost (all) (\$)	Revenue (\$)	Cost per Panel (\$)
Grid Connection	2,000,000	1,440,000	500,000	5.25
Generator	2,000,000	517,800	500,000	4.02

According to estimates by Agrotechnology, export quality boards can be produced for \$5/board (4'x8'x1/4") assuming a 25% rate of return, which qualifies the authors estimates to be on-target.

#### **11.5 Overall Cost Comparison**

An overall cost comparison between the two scenarios (breakeven and 25% return) for coir board and the current market cost for its alternative of plywood or OSB is contained within Table 13.

**Table 13:** Overall Cost Comparison

Scenario	Plywood/OSB	Coir Board, grid connected	Coir Board, generator
Breakeven	\$6.00/panel	\$4.60/panel	\$3.36/panel
25% Return	\$6.00/panel	\$5.25/panel	\$4.02/panel

The results illustrate that the production of coir board is able to undercut the current cost of its material counterpart in both scenarios. Therefore, illustrating that this is a good investment and is able to compete in the current market with little risk to the investor.

### **13. Outreach, Champions, and Partners**

As our research team is located in Berkeley, California it will be difficult for us to coordinate the implementation of the proposed plan. A local champion or partner in French Polynesia would be crucial in dealing with the daily challenges and obstacles the project will inevitably face. This person or organization can also work to promote the idea of sustainable materials and act as a source of knowledge for the local community. The appendix provides a summary of contacts at the Gump Station, in French Polynesia,

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United States non-profits, venture capitalist, and international groups whom may provide such a role. Refer to Appendix for detailed plan outreach plan and drafted letters.

## **14. Conclusions**

Although research was initially focused on sustainable building materials in French Polynesia, the scope of the project expanded to include the improvement of local livelihoods, embodied energy content, and greenhouse gas emissions. The expanded analysis allowed a more genuine focus on the topic of sustainability in remote island communities. A primary literature review revealed possible sustainable building materials. The alternative materials were reevaluated following a reconnaissance trip to French Polynesia. Subsequently, coir binderless board was selected as the most appropriate alternative technology to address issues of material sustainability, local livelihoods, and greenhouse gas emissions.

Various alternative schemes for implementation were evaluated. It is suggested that manufacturing plants be located on an outer island, along both an existing and proposed ferry route. As the coir binderless board would be replacing imported panel materials, an energy, greenhouse gas, and cost comparison was undertaken. The results show that the embodied energy content of coir board is equal to 5% of the total embodied energy content of plywood/OSB; neglecting energy consumed during shipment of plywood/OSB. Therefore, it reduces the embodied energy content of coir board to less than 5% because it does not utilize transport energy. As far as savings in CO<sub>2</sub> emissions, the results show that an 80% reduction can be achieved using coir from diesel rather than OSB/plywood. Concurrently, a reduction of 92% can be obtained by switching to coconut oil for manufacture of coir board. Lastly, cost per panel for both a breakeven and a 25% return on initial investment within the first year of operation is competitive with current market prices for comparable building materials such as plywood and OSB.

Subsequent research should focus on outreach and implementation. With regards to outreach, a local organization, non-profit, or governmental body must be willing to take the lead to ensure the proposed plans are implemented. Initial outreach activities have been undertaken; however additional communication is needed. Secondly, implementation remains a critical stage yet to be undertaken. A testing program would be necessary to win the support of the local builders and ensure the material is appropriate. Redefining the scope of the existing contract between the French Polynesian government and the University of California at Berkeley Gump Station would be the most appropriate route. Finally, a pilot scale plant would facilitate technology transfer among communities and ensure all technical, economic, and social concerns had been sufficiently addressed.

## 15. Acknowledgements

The authors would like to extend their gratitude to the following people and organizations for their generous assistance and support throughout the entire research period.

Blum Center, George Scharffenberger, Madelaine Fava, Brett Harper, Tim Duane Shay Boutillier, Taraina Pinson, The UC Berkeley Gump Station, Neil Davis, Valentine Brotherson, Susan Amrose, Professor Ashok Gadgil, Dr. Jan Van Dam, Dr. Jerrod Winandy, The Agricultural Service of FP, The Forestry Service of FP, The Ministry of Archipels of FP, The Ministry of Environment of FP, Stephane Defranoux, Matahiarii Tutavae, Charles Egretaud, and Benoit Layrle

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